NASA Contractor Report 3468

# Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project -

## Wing Planform Study and Final Configuration Selection, Summary Report

Staff of Boeing Commercial Airplane Company

CONTRACT NAS1-15325
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# Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project -

## Wing Planform Study and Final Configuration Selection, Summary Report

Staff of Boeing Commercial Airplane Company
*Boeing Commercial Airplane Company*
*Seattle, Washington*

Prepared for
Langley Research Center
under Contract NAS1-15325

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Scientific and Technical
Information Branch

1981

## FOREWORD

This document constitutes the summary report of the Wing Planform Study of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project. This part of the IAAC Project is focused on determining the effect of incorporating Active Controls Technology (ACT) early in the design of a commercial transport airplane. This project is one element of the NASA Energy Efficient Transport Program, with the common objective of improving the energy efficiency of commercial transports.

NASA Technical Monitors for this task were D. B. Middleton and R. V. Hood of the Energy Efficient Transport Project Office at Langley Research Center.

The work was accomplished within the Preliminary Design Department of the Vice President-Engineering organization of the Boeing Commercial Airplane Company. Key contractor personnel who contributed were:

| | |
|---|---|
| G. W. Hanks | Program Manager |
| H. A. Shomber | IAAC Project Manager |
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| M. T. McIntosh | Structures Technology |
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| J. D. Brown | Weight Technology |

During this study, principal measurements and calculations were made in customary units and were converted to Standard International units for this document. IAAC configuration model numbers (768-102, -103, -104, -105, -106, and -107) appear, as applicable, in the lower right-hand corner of each illustration.

## CONTENTS

## SUMMARY

This report summarizes results of the final configuration task of the "Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport" Project. The objective of this work was to determine how Active Controls Technology (ACT) in combination with altered wing planforms affects fuel efficiency for a 197-passenger, medium-range commercial air transport. Three configurations having different combinations of wing sweep and span were developed in the study. These, together with the Initial ACT Configuration developed in an earlier study (NASA CR-3304 and NASA CR-159249), were compared to a Conventional Baseline Configuration to evaluate fuel efficiency trends. The Conventional Baseline Configuration is a state-of-the-art transport selected and defined in a previous task (NASA CR-159248). The best configuration studied was then resized to the same mission range as the Conventional Baseline Configuration and is designated the Final ACT Configuration. Throughout the study, non-ACT technology levels were held constant for all configurations. Wing trailing-edge control surfaces were employed for load alleviation and flutter control as appropriate. It was assumed that all beneficial ACT functions could be implemented with reliability appropriate for commercial operation.

As the study progressed, it became evident that an aspect ratio (AR) 12 configuration, with the largest span of those considered, had the best fuel efficiency and was therefore selected as the basis for the Final ACT Configuration. The detailed analysis then focused on the AR 12 configuration and included trade and sensitivity studies relating to the Final ACT Configuration selection. Relative to the Baseline, the Final ACT Configuration required 10% less block fuel for the design mission, of which 6.5% is attributed to the use of ACT and 3.5% to wing span increase.

The major ACT benefit resulted from balancing the airplane and sizing the horizontal stabilizer from control consideration only; i.e., operation of the airplane depends upon the pitch-augmented stability (PAS) function; i.e., it is crucial to continued safe flight. The PAS and angle-of-attack limiting (AAL) functions together accounted for 6% increased fuel efficiency on the Final ACT Configuration—about 0.5% was from wing-load alleviation (maneuver-load control)—for a total fuel benefit due to ACT of 6.5%. A detailed review of flight-critical PAS/flight-crucial PAS should be undertaken to determine whether there is a beneficial cost/performance trade.

The ACT configurations exhibited center-of-gravity ranges about 10% aft of the Conventional Baseline Configuration. Integrating the landing gear into these configurations required relatively large side-of-body chords for the increased wing span ACT configurations. This resulted in a structurally efficient inboard wing box, which allowed the wing span to be increased with only a modest weight increase. This planform characteristic may also benefit non-ACT configurations.

The airplane performance benefits identified in the IAAC Project to date are the result of a degree of dependence upon control systems that is well beyond any currently certified commercial airplane. Considerable design, development, and laboratory and flight test must precede a commitment to commercial application. Work currently underway on the IAAC Project is the beginning of this necessary development and test.

# INTRODUCTION

Although active controls are used in several existing commercial transports, those applications are either very limited in scope or were added after the airplane was in production. Typically, these additions were made either to overcome an unanticipated difficulty or to add capability to the airplane. A considerable body of evidence suggests that the greatest benefit from application of ACT to a transport airplane will result from incorporating ACT early in the design process. Although this evidence strongly indicates a benefit, estimates of this benefit lack credibility because there have been no such applications of ACT.

The principal objective of the IAAC Project, therefore, was to assess the benefits associated with design of a commercial ACT transport. The potential benefit was shown to be very significant. During development of this benefit assessment, certain technical risk areas became clear. This led to the second objective of the IAAC Project, which was to identify technical risk areas and to recommend appropriate test and development programs. The final objective, to pursue resolution of these risk areas to the maximum possible extent within project resource limitations, is the focus of the current IAAC Project work.

## IAAC PROJECT

The IAAC Project comprises three major elements, as discussed in Reference 1 and shown in Figure 1. The first, Configuration/ACT System Design and Evaluation, addressed the design of an ACT transport, to specific design requirements and objectives (DRO), in sufficient detail to clearly identify the performance and economic benefits associated with the use of ACT. This airplane design process incorporated all beneficial ACT systems and yielded a performance and economic assessment of those ACT systems. Current technology implementation was assumed in order to incorporate little or no technical risk, from a systems viewpoint, and to avoid compromise to the credibility of the overall ACT evaluation.

In parallel, work was initiated on the second major element, Advanced Technology ACT Control System Definition, to identify potential improvements through the use of optimal control law synthesis techniques and/or advanced technology components for the implementation of ACT systems.

Further details of the Wing Planform Study results and the Final ACT Configuration characteristics are contained in the body of this report and in the IAAC Wing Planform Study and Final Configuration Selection Final Report (ref 2).

Following the benefits assessment, work began on the final major element, Test and Evaluation. The objective of that work was to reduce selected real or perceived technical risks associated with implementation of ACT.

### Technical Approach

A modern Conventional Baseline Configuration, without any significant application of ACT, was developed as a yardstick against which the benefits of ACT could be measured. This reference airplane configuration also established the design mission for the ACT configurations. The technology of the ACT airplanes designed under this project was fixed at the level established by the Baseline Configuration, except for ACT.

The airplane configuration design work proceeded under the assumption that any beneficial ACT function could be implemented with appropriate reliability and availability. The Current Technology ACT Control System Definition Task proceeded, in parallel, to determine a suitable low-technical-risk implementation. The first configuration development step of the IAAC Project was the Initial ACT Configuration Design Task.

Characteristics of these first two configurations are briefly summarized in the next few pages.

**Wing Planform Study Task**

The second configuration development step of the IAAC Project, the Wing Planform Study Task, is the subject of this summary report. The objectives of this work were to determine the effects of changing wing planform, in combination with active controls functions, on the fuel efficiency of commercial transports and to select a Final ACT Configuration. Figure 1 shows the relationship of this work, within the Configuration/ACT System Design and Evaluation element, to the total IAAC Project. This report summarizes the work accomplished; Reference 2 contains more detail.

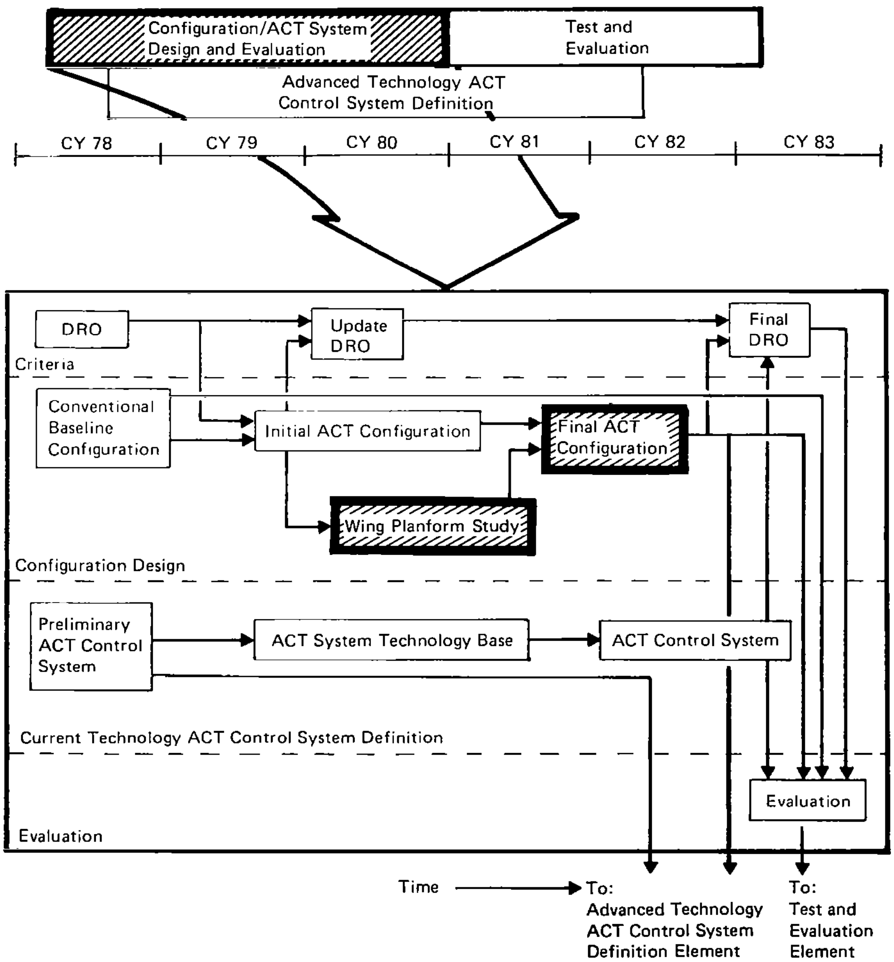



*Figure 1. Relationship of Wing Planform Study and Final ACT Configuration Task to the Overall IAAC Project*

## CONVENTIONAL BASELINE CONFIGURATION

Domestic trunk operations use about 28.5 billion ℓ (7.5 billion gal) of fuel annually. One airplane-type (727) fleet uses one-half as much fuel as all other types of airplanes in domestic trunk operation combined; e.g., approximately 9.5 billion ℓ (2.5 billion gal) annually (ref 3). The greatest potential leverage of this study on domestic trunk air carrier fuel consumption, therefore, results from the design of an ACT airplane that could perform the mission of that fleet. The Conventional Baseline Configuration selected for this study is a 197-passenger (plus cargo), nominal 3590 km (1938 nmi) design range airplane and is projected to satisfy the selected mission, considering market demands for the post-1985 period.

This selection allowed Boeing to apply a considerable amount of available analytical and test data derived during earlier preliminary design efforts. The existing data base was reviewed and additional analysis was conducted as necessary to complete the technical descriptions. The resulting Baseline Configuration, shown in Figure 2, uses a double lobe, but nearly circular, body with seven-abreast seating. It has an 8.71 aspect ratio (AR), 31.5 deg swept wing, a T-tail empennage, and two wing-mounted CF6-6D2 engines. The lower lobe has volume for 22 LD-2 or 11 LD-3 containers, plus bulk cargo. Operationally, passenger and cargo loading, servicing provisions, taxi and takeoff speeds, and field length characteristics are all compatible with accepted airline and regulatory provisions.

The Baseline Configuration uses state-of-the-art aluminum structure with advanced aluminum alloys and a limited amount of graphite-epoxy secondary structure. Modern systems are used, including advanced guidance, navigation, and controls, that emphasize application of digital electronics and advanced displays.

Further characteristics and performance details are contained in the Conventional Baseline Configuration Task Final Report, Reference 4.

| | |
|---|---|
| Configuration | |
| Passengers | 197 mixed class, 207 all tourist |
| Containers | 22 LD-2, or 11 LD-3 |
| Engines | 2 (CF6-6D2) |
| Design mission | |
| Cruise Mach | 0.8 |
| Range | 3590 km (1938 nmi) |
| Takeoff field length | 2210m (7250 ft) |
| Approach speed | 70 m/s (136 kn) |
| Noise | FAR 36, Stage 3 |
| Flying qualities | Current commercial transport practice |
| Airplane technology | Current commercial transport practice (aerodynamics, structural, propulsion, etc.) |

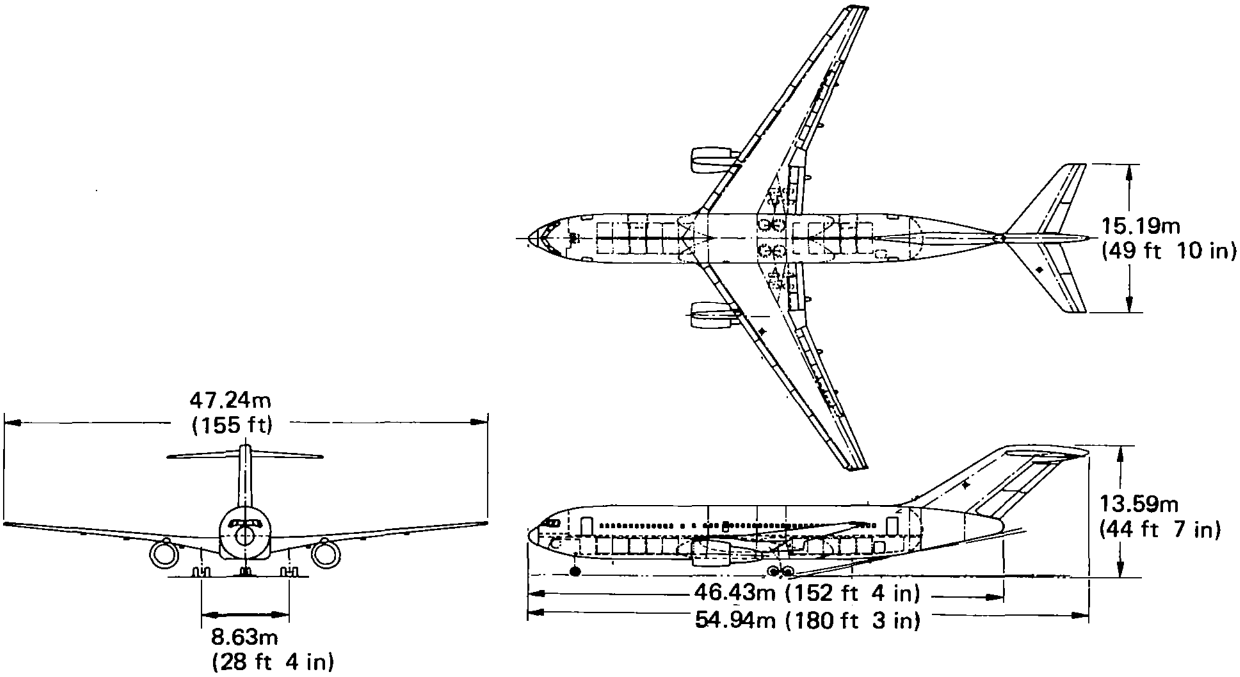



*Figure 2. Baseline Configuration*

## INITIAL ACT CONFIGURATION

The first configuration development step of the IAAC Project was the Initial ACT Configuration Design Task. The objectives of this task were to identify the performance and economic benefits of ACT as applied to the Conventional Baseline, without change in wing planform, and to establish the design approach for subsequent steps in the development of the Final ACT Configuration. Throughout the Configuration/ACT System Design and Evaluation element, the technology levels for structures, propulsion, and aerodynamics were held constant at the levels established by the Conventional Baseline Configuration so that incremental benefits from ACT applications could be assessed.

Development of the Initial ACT Configuration was constrained to meet the specific objectives of this task most efficiently. One very important constraint was the maintenance of wing planform and area in order to understand the impact of ACT on an airplane designed to the same aerodynamic performance level as the Baseline. The Baseline Configuration takeoff gross weight, propulsion system, and empennage planform were also maintained to enable the ACT performance increment to be assessed with significantly fewer resources than would otherwise be required. The Initial ACT Configuration was not resized for constant payload/range. Therefore, reductions in block fuel and range increase at constant payload were measures of performance improvement. Major configuration options; e.g., cargo containers and volume and provisions for upper- and lower-deck pallet doors, were maintained to ensure a versatile and economical commercial transport.

The principal dimensions and general arrangement of the Initial ACT Configuration are shown in Figure 3. The configuration is a twin-engine, low-wing commercial transport with a design range of approximately 4061 km (2193 nmi), a payload of 197 passengers (in mixed-class accommodations), and 22 LD-2 containers. Two General Electric CF6-6D2 engines, in wing pylon-mounted nacelles, power the airplane. Structural materials and design practice are conventional, using aluminum alloy for the primary structure with a limited amount of graphite-epoxy secondary structure, and other materials such as high-strength steel for landing gear components.

The Initial ACT Configuration, with a 10% farther aft cruise center of gravity (cg) and a 45% smaller horizontal stabilizer than the Conventional Baseline, requires 6% less block fuel at the design range. Further characteristics and performance details are contained in the Initial ACT Design Study Final Report, Reference 5.

| | |
|---|---|
| Configuration | |
| Passengers | 197 mixed class, 207 all tourist |
| Containers | 22 LD-2, or 11 LD-3 |
| Engines | 2 (CF6-6D2) |
| Design mission | |
| Cruise Mach | 0.8 |
| Range | 4061 km (2193 nmi) |
| Takeoff field length | 2118m (6950 ft) |
| Approach speed | 68.6 m/s (133.4 kn) |
| Noise | FAR 36, Stage 3 |
| Flying qualities | Current commercial transport practice |
| Airplane technology | Current commercial transport practice (aerodynamics, structural, propulsion, etc.) except for ACT |

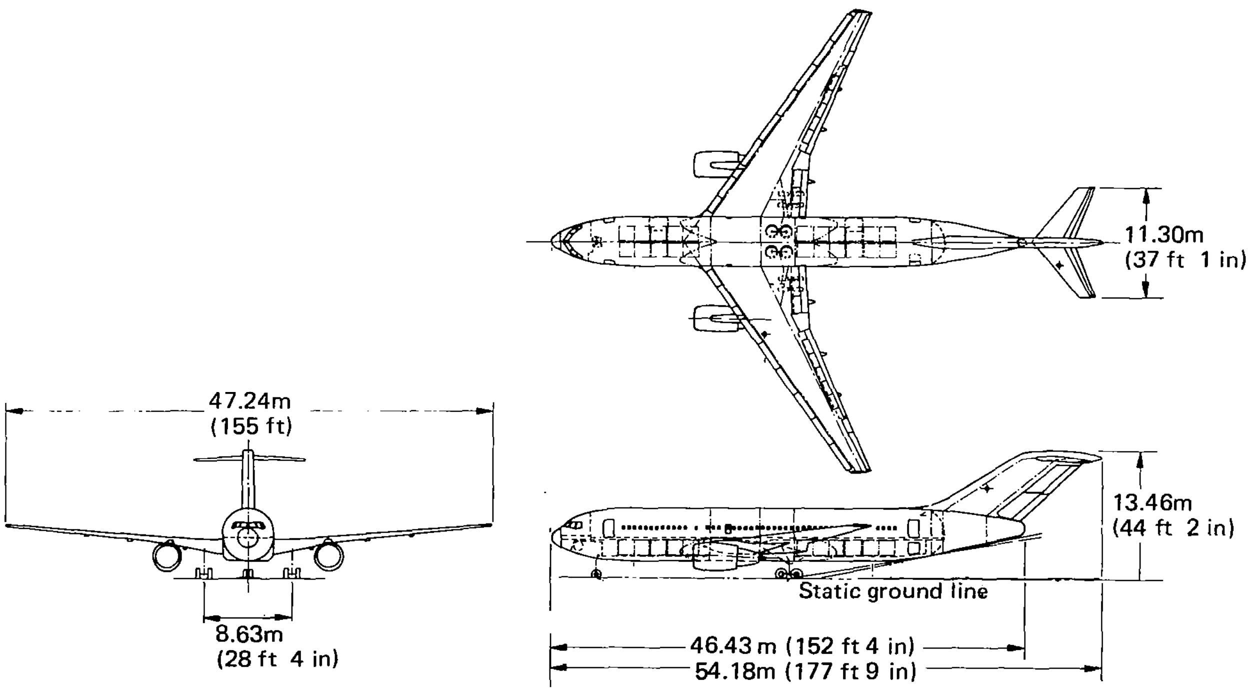



*Figure 3. Initial ACT Configuration*

## WING PLANFORM STUDY OBJECTIVES AND TECHNICAL APPROACH

The objectives of the Wing Planform Study were to:

- Determine the effect of changes in wing planform (aspect ratio and sweep) on the overall performance of an airplane incorporating ACT functions from the outset of the design process: wing thickness was varied as necessary to maintain constant cruise speed

- Identify the impact of key assumptions in the technical approach on study results, where significant, through sensitivity analyses

- Select a Final ACT Configuration from the Initial ACT data in combination with results of the Wing Planform Study

The configuration development portion of the IAAC Project (fig. 4) began with the selection of the Conventional Baseline Configuration. This airplane is a modern commercial transport designed to a payload/range mission that could potentially serve the segment of the domestic airline market that uses the greatest amount of fuel. This airplane selection established the specific mission and the technology in every aspect except ACT. The DRO for this airplane and its systems was then modified as required to accommodate the ACT functions to be studied. The Initial ACT Configuration showed the benefit of incorporating active controls in the design, without a change in the wing planform, as previously discussed.

In the work summarized herein, three additional active controls configurations were designed to the same gross weight as the Baseline and the Initial ACT Configurations, but with variations in wing planform. The changes in wing planform were made in such a way that cruise speed was held constant and the airplane could be assembled without a change in the landing gear concept. The empennage type was maintained, but the empennage area was adjusted as required to yield three airplanes balanced to the same philosophy as the Initial ACT; i.e., from control considerations only. With fuel efficiency as the primary figure of merit, the Final ACT Configuration was selected and resized to meet the mission of the Conventional Baseline Configuration.

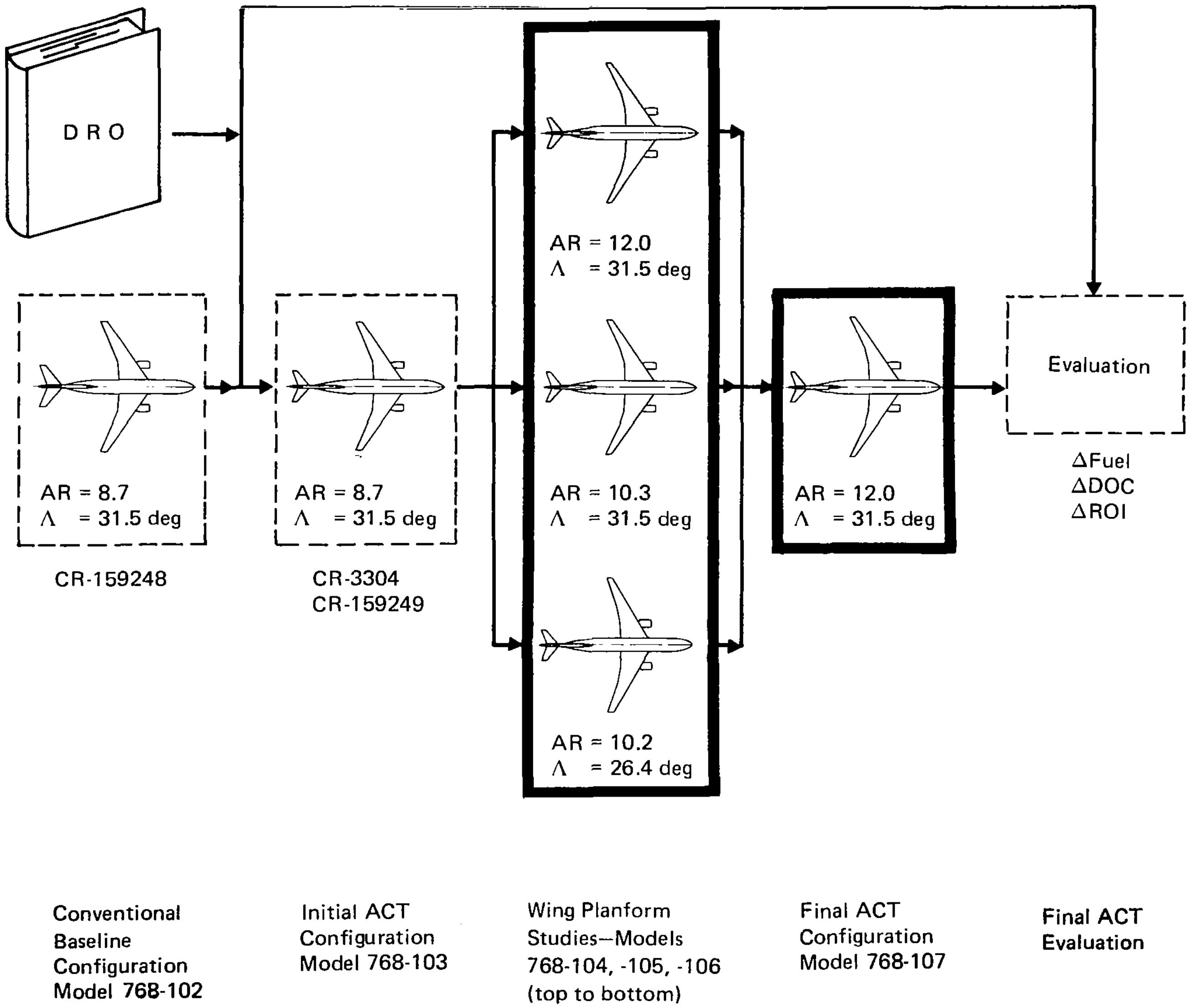



*Figure 4. ACT Configuration Evolution*

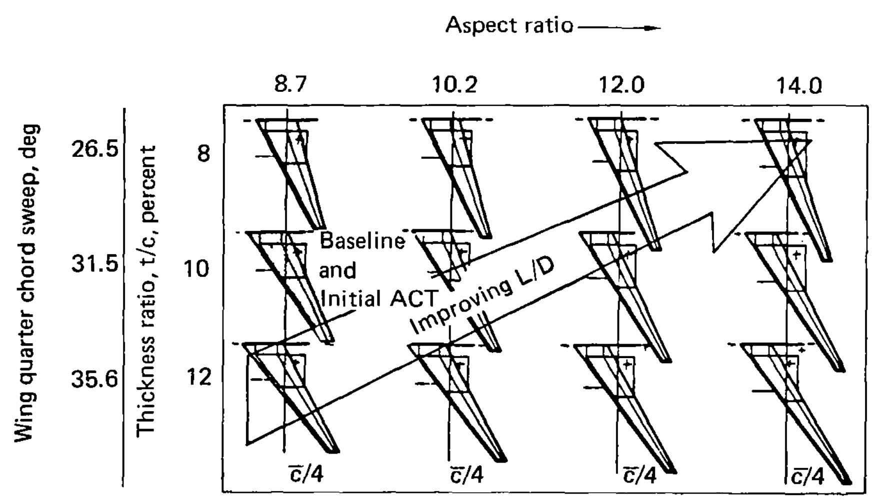
## MATRIX OF CANDIDATE WING PLANFORMS

Prior to selecting the specific airplanes to be designed as part of the Wing Planform Study, a matrix of wing geometry candidates was selected. This matrix included plus and minus 5 deg changes in wing sweep and aspect ratios as high as 14 (based on trapezoidal wing area), as shown in Figure 5(a). Over this region of wing geometry, the ratio of lift to drag (L/D) improves as sweep is reduced and as aspect ratio is increased. This effect includes thickness adjustments as required to maintain cruise speed.

Figure 5(b) illustrates that the trend in airplane operating empty weight over this region of wing geometry has a direction of goodness almost opposite that of increasing L/D. That is, for airplanes with about the same wing area, span reduction and/or increased thickness results in lighter wings.

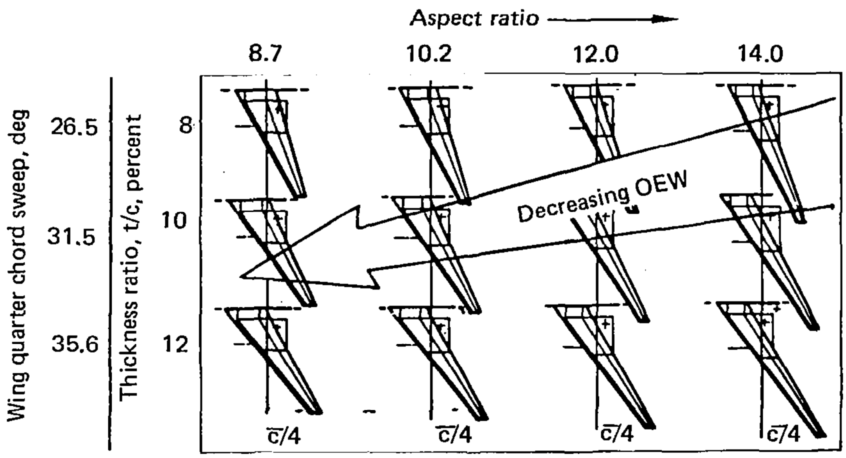
In the Wing Planform Study, the type of landing gear that was considered acceptable was constrained. To meet the airplane design requirements relative to ground handling, the main landing gear footprint must remain sufficiently far aft of the most aft cg to prevent tip-up at brake release. This problem is especially severe for twin-engine airplanes with the engines mounted under the wing. The problem stems from the high thrust-to-weight ratio typical of twin-engine transports and the low thrust line. When that consideration is combined with the relatively far aft cg locations possible with the active controls design, the problem is compounded. Finally, as sweep increases, a combination of wing sweep and aspect ratio is reached where the size of the inboard trailing-edge extension necessary to contain a wing-mounted gear becomes excessively large. This is reflected by the direction of the increasing gear complexity arrow in Figure 5(c). A solution to the dilemma of landing gear-wing integration is to incorporate fuselage (i.e., body-mounted) landing gear. This option was ruled out in the Wing Planform Study to preclude spending an inordinate amount of engineering time designing the landing gear fuselage interface.

Figure 5(d) shows the three planforms that were selected for the Wing Planform Study and their relationship to the Baseline and Initial ACT Configuration planforms.

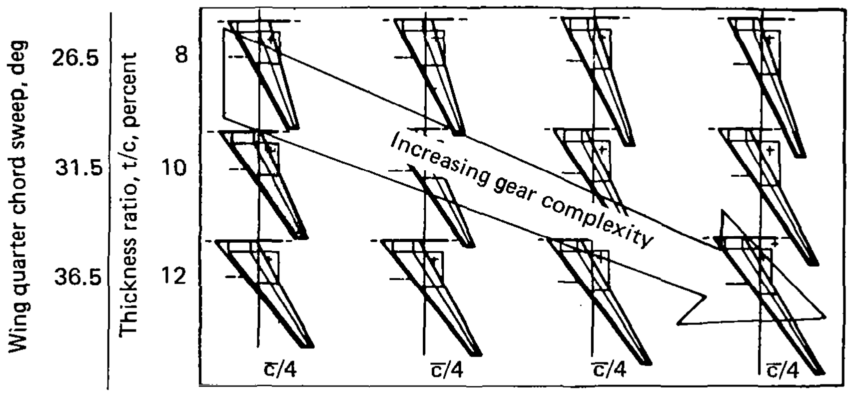



(a) L/D Trends

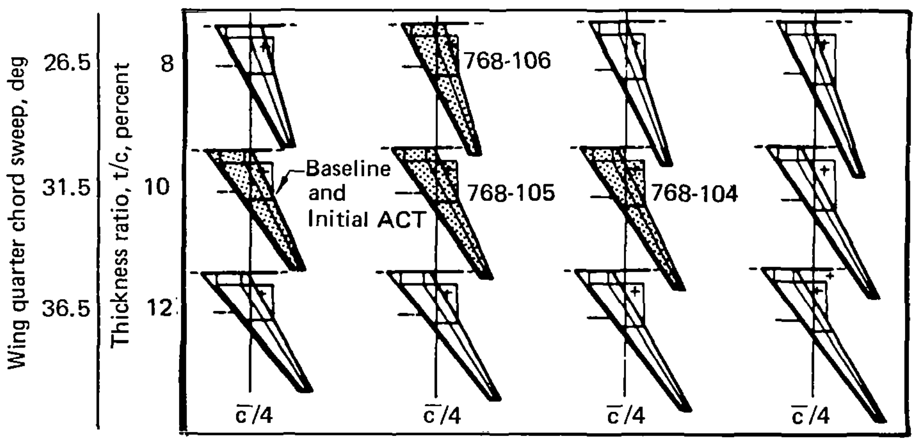
*Figure 5. Matrix of Candidate Planforms*




(b) Structural Weight Trends




(c) Landing Gear Complexity Trends




(d) Selected Wing Planforms

*Figure 5. Matrix of Candidate Planforms (Continued)*

## WING PLANFORM COMPARISON

Airplane configurations were developed with the three selected wing geometries. These airplanes were designed to have the same takeoff gross weight and propulsion system as the Baseline and Initial ACT Configurations. The wing areas were sized for about the same approach speed. Fuselage shape and size and passenger and lower lobe container arrangement are identical to the Initial ACT Configuration. Assuming the same cg range due to payload and fuel shift, the wings were located on the fuselage with the cruise cg position at 35% mean aerodynamic chord (MAC). The three wing planforms are shown overlaid with the Initial ACT Configuration wing in Figure 6. Note that the resulting wing planforms are very similar inboard of the engine, with minor variations in chord outboard. Horizontal and vertical tail geometries were maintained with sizes adjusted according to stability and control requirements. The landing gear configuration is the same as the Initial ACT Configuration, except for a cantilever support instead of a landing gear beam support on the AR 10.2, sweep ($\Lambda$) = 26.5 deg configuration.

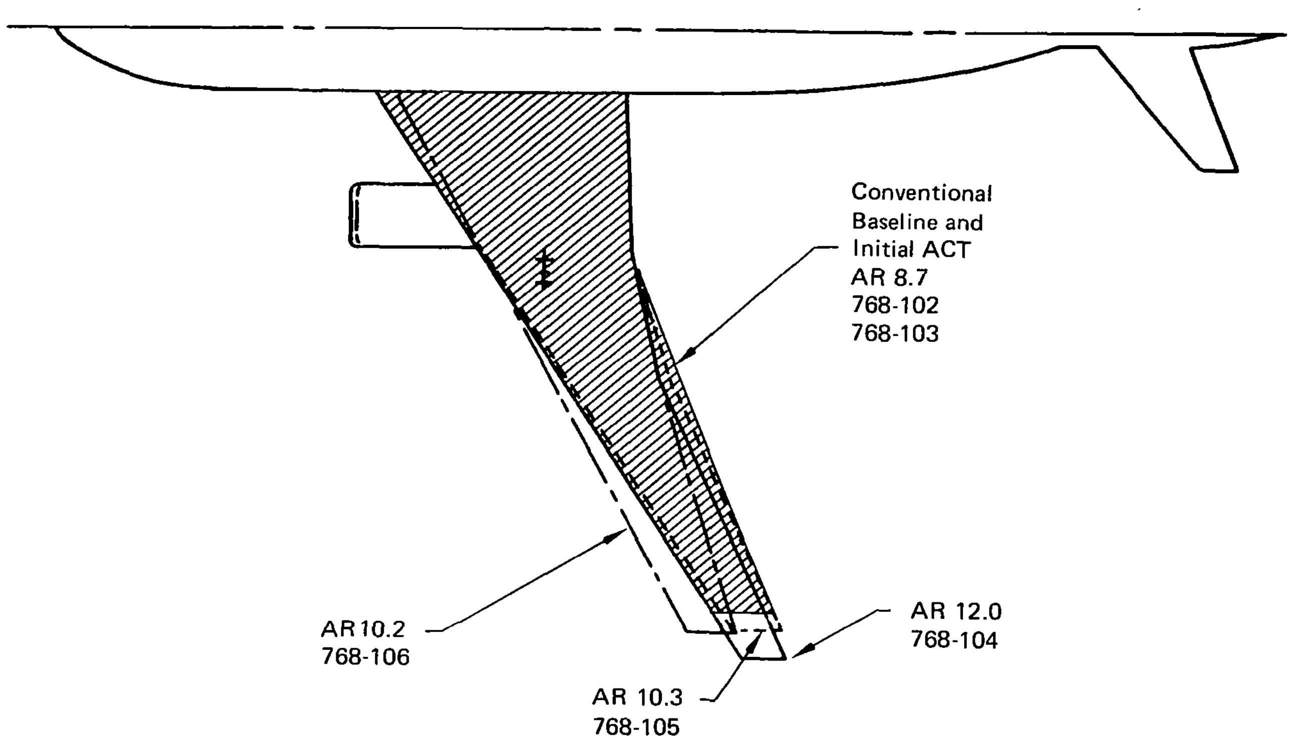



*Figure 6. Wing Planform Comparison*

## ACTIVE CONTROLS FUNCTIONS

Selection of active controls functions for the Wing Planform Study Configurations was based on a preliminary assessment of the expected benefit in airplane weight or drag reduction. No formal quantitative risk-versus-benefit evaluation was made prior to selecting the functions. Analysis of the 768-104 (AR 12, $\Lambda = 31.5$ deg) configuration resulted in the incorporation of the following beneficial ACT functions:

- Pitch-augmented stability (PAS)—The PAS function augments the airplane longitudinal stability to provide acceptable flying qualities. Long-period (phugoid) and short-period (static stability) augmentation are included. The action of the PAS also provides significant reduction of the low-frequency wing gust loads.

- Lateral/directional-augmented stability (LAS)—The LAS function is a conventional yaw damper identical to that of the Baseline Configuration.

- Angle-of-attack limiter (AAL)—The AAL function prevents the airplane from exceeding a limiting angle of attack. By limiting angle of attack to a small margin beyond that for maximum lift, it is possible to reduce the horizontal tail size required to provide nosedown control margin for stall recovery.

- Wing-load alleviation (WLA)—Only one of the WLA function submodes was determined to be beneficial for this configuration:

  - Maneuver-load control (MLC)—The MLC function reduces the wing vertical bending moment in longitudinal maneuvers and low-frequency gusts by deflecting the outboard ailerons to redistribute the wing loads.

High-frequency gust-load alleviation (GLA) and flutter-mode control (FMC) were also considered in the design of the Wing Planform Study Configurations but were not sufficiently beneficial to merit their inclusions for the 768-104.

Use of ACT to meet longitudinal stability requirements allowed the horizontal tail to be sized by only controllability requirements, as shown in Figure 7. The aft cg controllability limit was set by the requirement to develop stall recovery pitching moments at the maximum angle of attack achievable. Without control system provisions to limit the maximum angle of attack, controllability becomes critical for a T-tail configuration at very large post-stall angles of attack. By providing angle-of-attack limiting, the required recovery pitching moment could be reduced to the level necessary for recovery from an angle of attack only a small increment above the angle of attack required to develop maximum lift. Thus the tail size was significantly smaller for any particular aft cg for the airplane with an alpha limiter. The limiting aft cg condition, shown in Figure 7, is for normal stall recovery with an alpha-limiting system.

Typically, forward cg limits are set by either landing approach or takeoff rotation. The takeoff rotation requirement for mistrim was reduced by providing a "green band" that limited the range of acceptable trim settings and a warning system to preclude takeoff with trim set outside this range. Consequently, the Initial ACT Configuration tail size was not critical at the forward cg limit.

The vertical tail size was also set by control requirements; i.e., engine-out control, with a yaw damper included as in the Conventional Baseline Configuration to improve the lateral/directional dynamics.

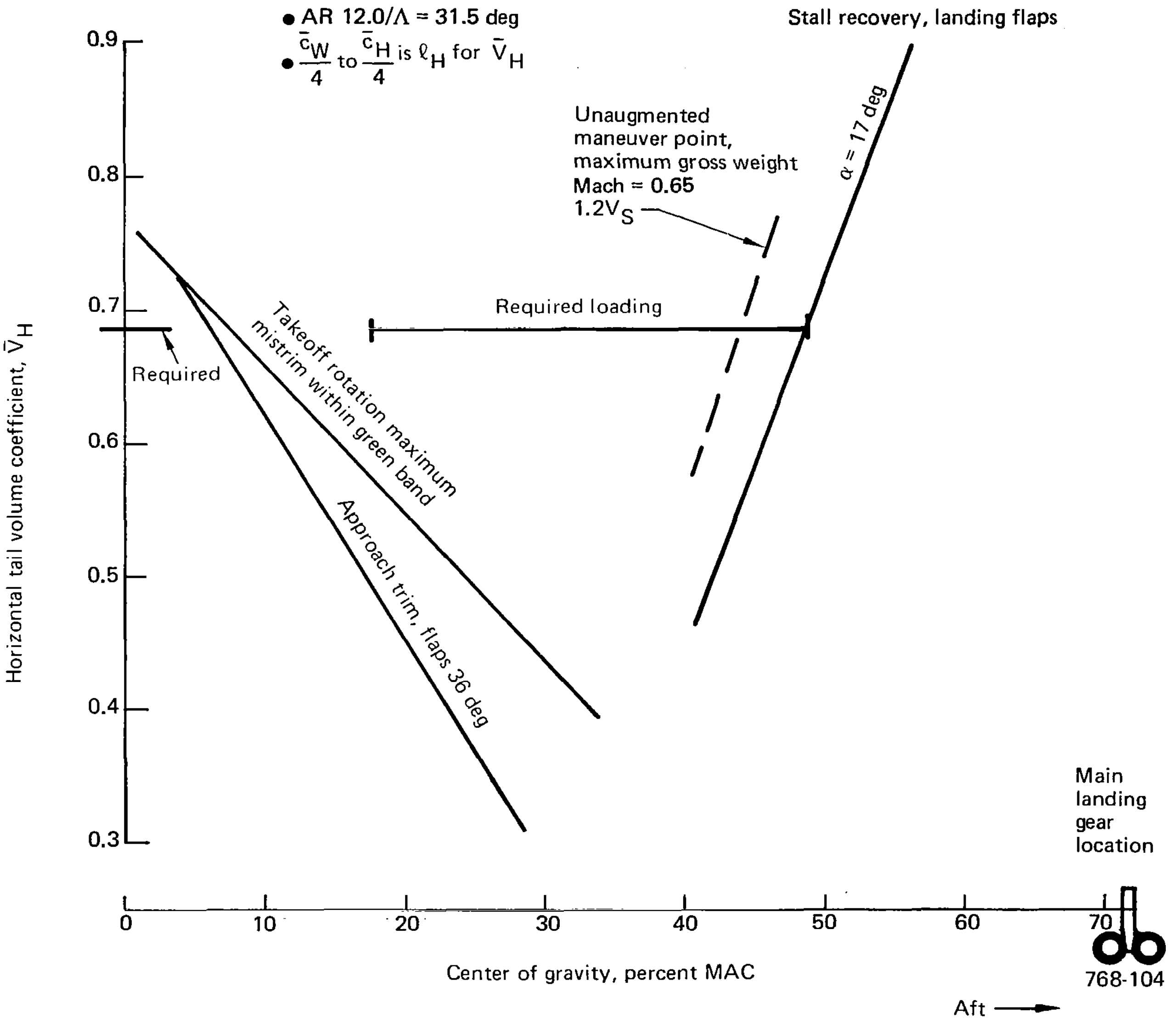



*Figure 7. Horizontal Tail Size Requirements, Model 768-104*

## AUGMENTED SHORT-PERIOD CHARACTERISTICS

Augmented longitudinal short-period characteristics for Model 768-104 (AR 12) are shown in Figure 8. Figure 8(a) shows the takeoff and landing characteristics to meet the selected Level 1 requirements, based on the Military Airplane Flying Qualities Specification (ref 6). For reference, the unaugmented airframe, which falls outside the Level 3 requirement boundary, also is shown.

Figure 8(b) shows the en route configuration characteristics for a number of flight conditions spanning the operational flight envelope. All fall within the Level 1 boundary. For reference, the unaugmented cruise configuration is shown for two weight extremes. Note their proximity to the Level 2 boundary. All augmented characteristics also exhibit satisfactory damping.

Because the other study configurations had very similar unaugmented airframe characteristics, their augmentation requirements were not further investigated. The unaugmented airframe characteristics of all the wing planform configurations have longitudinal handling qualities that are unsatisfactory even for emergency operation. This leads to the requirement for a crucial pitch-augmentation system.

A trade study was conducted to examine tail size increase, loading restriction, flight envelope restriction, or a combination of these, which would result in minimum acceptable unaugmented characteristics that could be augmented to a satisfactory level. This could be accomplished with a critical pitch-augmentation system rather than a crucial system. The trade study revealed that restricting the aft cg limit by approximately 1.5% MAC, or increasing the horizontal tail size by approximately 5%, and restricting the maximum operating altitude (with failed PAS) to about 9140m (30 000 ft) would achieve the desired characteristics. It is estimated that the penalty in block fuel of the restricted loading or tail size increase would be about 0.5%.

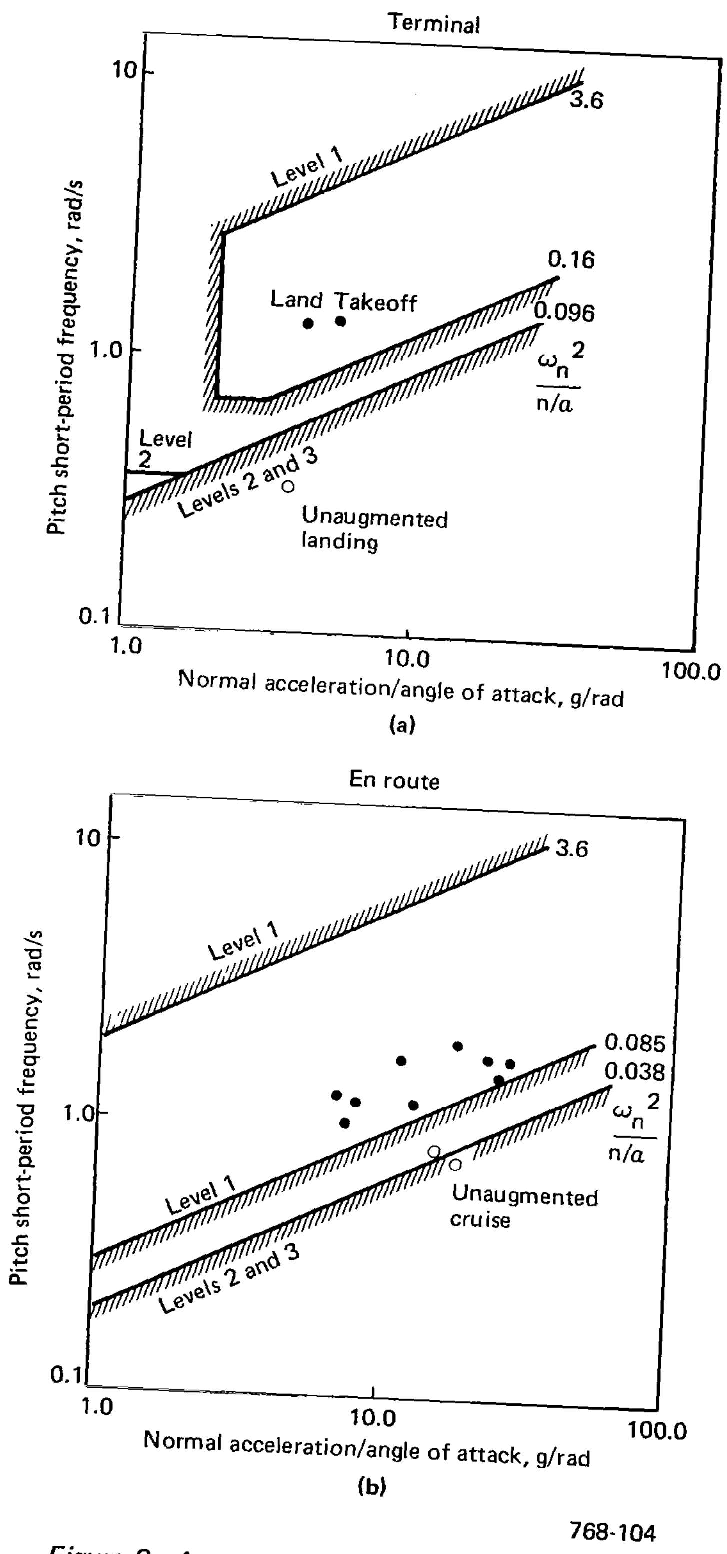



*Figure 8. Augmented Short-Period Characteristics*

## WING DESIGN

A key element of the design of a commercial jet transport is the integration of the main landing gear into the configuration. The landing gear must be placed sufficiently far aft of the aft cg limit to meet ground handling requirements. The structure must be able to carry both taxi and impact loads and provide adequate stiffness for stability. It is usually desirable to have the gear completely faired into the wing-body contours when it is retracted. This landing gear integration problem becomes even more complex as wing aspect ratio increases for a given sweep and thickness. Consequently, the inboard part of the wing planform is essentially the same for all the ACT configurations studied.

The wing planforms for the Model 768-104 (AR 12) configuration and the Baseline/Initial ACT Configuration are compared in Figure 9(a). The planforms are shown with the 35% MAC points aligned.

The increased aspect ratio for the AR 12 configuration was achieved by increasing the span and taper of the Baseline wing while holding the wing area, root chord, and thickness-to-chord ratio (t/c) distribution nearly constant. Note that the planforms inboard of the nacelle are nearly the same. The increased aspect ratio was achieved by reducing the chords outboard of the nacelle as the span was increased, to hold the wing area essentially constant, hence effectively increasing wing overall taper. The wing-box geometry and maximum box depth are similar in the inboard wing, where design loads and flutter stiffness requirements are highest, but are reduced in the outboard wing. Figure 9(b) shows a comparison of wing-box cross sections (cut normal to the elastic axis). These cuts show that at the side of body and at the nacelle there is little difference in the box depth, but there is significant reduction at the 60% span.

This configuration is structurally more efficient than a configuration with the same aspect ratio and wing area but with reduced root chord and taper. The outboard wing chords are shorter, thus wing-tip aeroelastic washout is greater, due to reduced outboard wing stiffness, and the design airload center of pressure is further inboard (relative to the wing tip). Less nosedown jig twist is required to maintain the same cruise span loading than on a lower aspect ratio wing.

This high aspect ratio wing has reduced stiffness outboard, with a distinctly different flutter mode and a more critical dynamic gust response outboard. However, the flutter and dynamic gust response considerations require only about 258.5 kg (570 lb) and 63.5 kg (140 lb), respectively, of additional wing structural material.

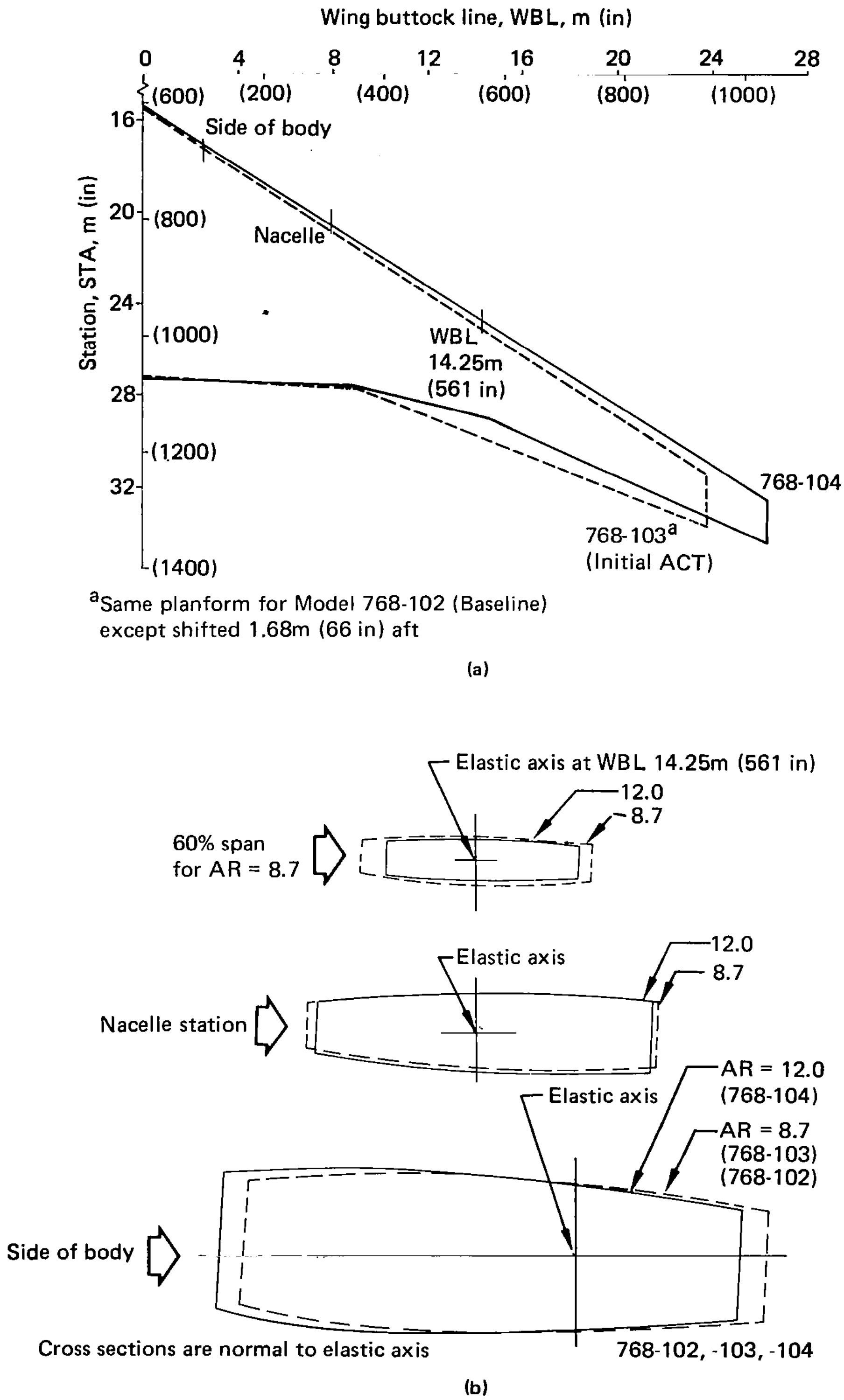



*Figure 9. Wing Planform and Wing-Box Comparisons*

## WING LIFT DISTRIBUTION

Compared to the Initial ACT (AR 8.7), the spanwise center of pressure for the critical maneuver condition is shifted inboard with respect to the wing tip for the AR 12 configuration, as shown in Figure 10(a). The AR 12 configuration has reduced outboard wing stiffness, which results in increased wing-tip washout for this configuration. A similar trend was predicted for all planform study wings due to the shorter outboard wing chords (with associated reduced thickness dimension) for these configurations.

Built-in wing twist (jig twist) was adjusted in the outboard wing for the planform study configurations so that all wings exhibit the same span loading in 1g cruise flight.

Figure 10(b) shows the resulting wing maximum box depths for the Baseline/Initial ACT (AR 8.7) wing and the AR 12 wing. The higher aspect ratio wing exhibits a slightly increased box depth from the nacelle location inboard where the design loads are highest, as shown in Figure 10(b), and a reduced box depth outboard. The increased structural material for strength, due to larger inboard wing loads, and the favorable inboard wing-box depth resulted in increased inboard torsional stiffness, which had a very favorable effect on the flutter characteristics of the wing.

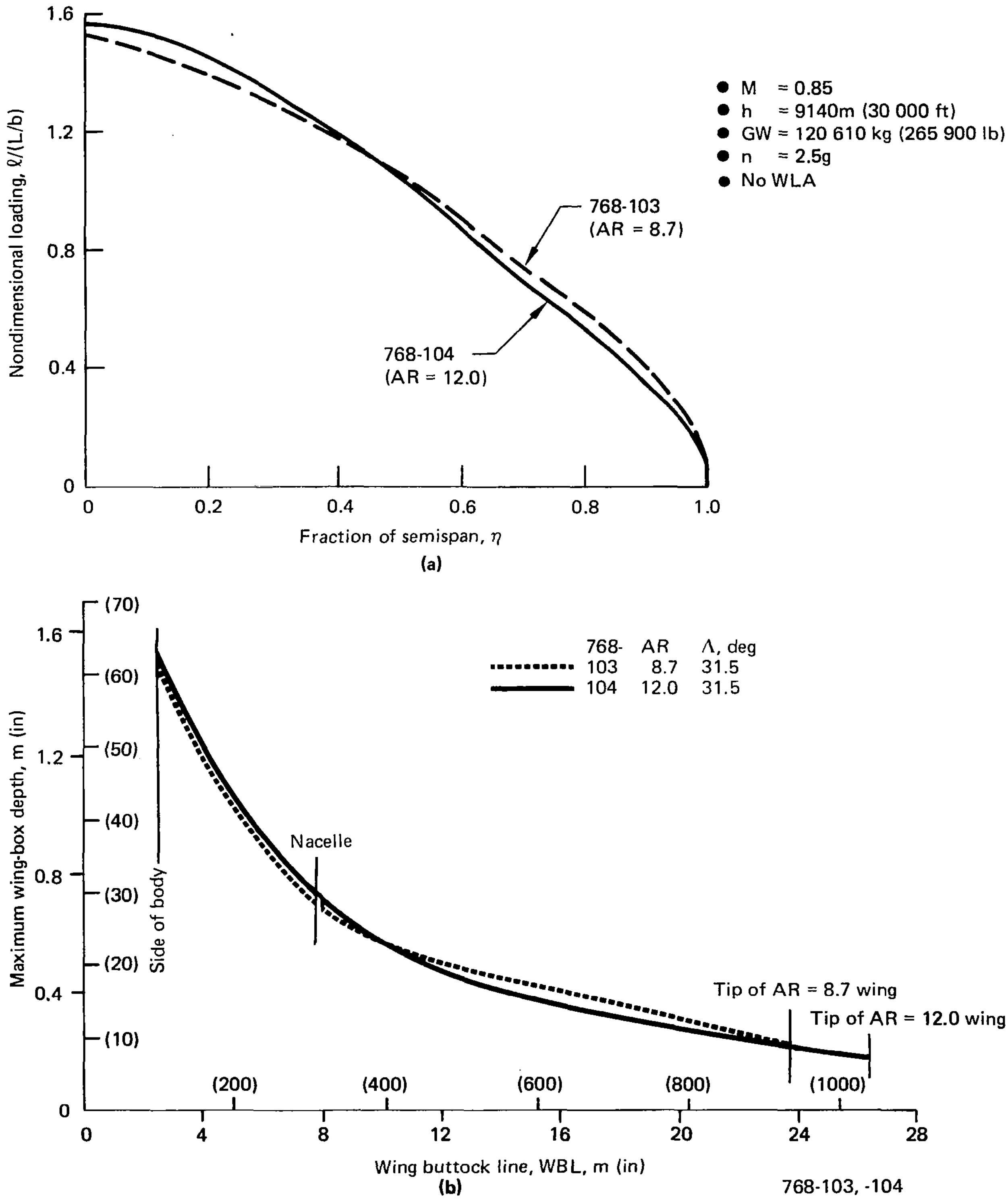



*Figure 10. Maximum Wing-Box Depths and Wing-Lift Distribution Comparisons*

## WING MATERIAL REQUIREMENTS

The wing-box structural material requirements result from many considerations, including ground conditions, maneuver, gust, fatigue, and flutter. Different parts of the wing are designed by different requirements. Figure 11(a) and 11(b) shows the upper and lower **surface** structural material requirements for the AR 12 configuration. Maneuver and gust formula conditions, which were used for initial wing sizing estimates, were conservative for most of the wing. However, structural material was added in the wing lower surface to satisfy fatigue and dynamic gust requirements. No structural material was added to the wing surfaces for flutter stability requirements.

Figure 11(c) and 11(d) shows the front and rear **spar** structural material requirements for the AR 12 configuration. The materials shown in this figure provide flutter clearance to $1.2V_D$. Note the differences in ordinate scales in this figure. The indicated flutter material was required to prevent an explosive 7-Hz outboard wing symmetric flutter mode. Because this is a high-frequency mode, controlling it beyond $V_D$ with flutter-mode control would have required very high rate actuation with associated adverse weight impact on the hydraulic system and outboard wing. It was determined to be more beneficial to provide the clearance passively with modest additional spar structural material. No additional structural material was necessary to control inboard wing flutter for this configuration due to the adequate structural stiffness that resulted from meeting the strength requirements.

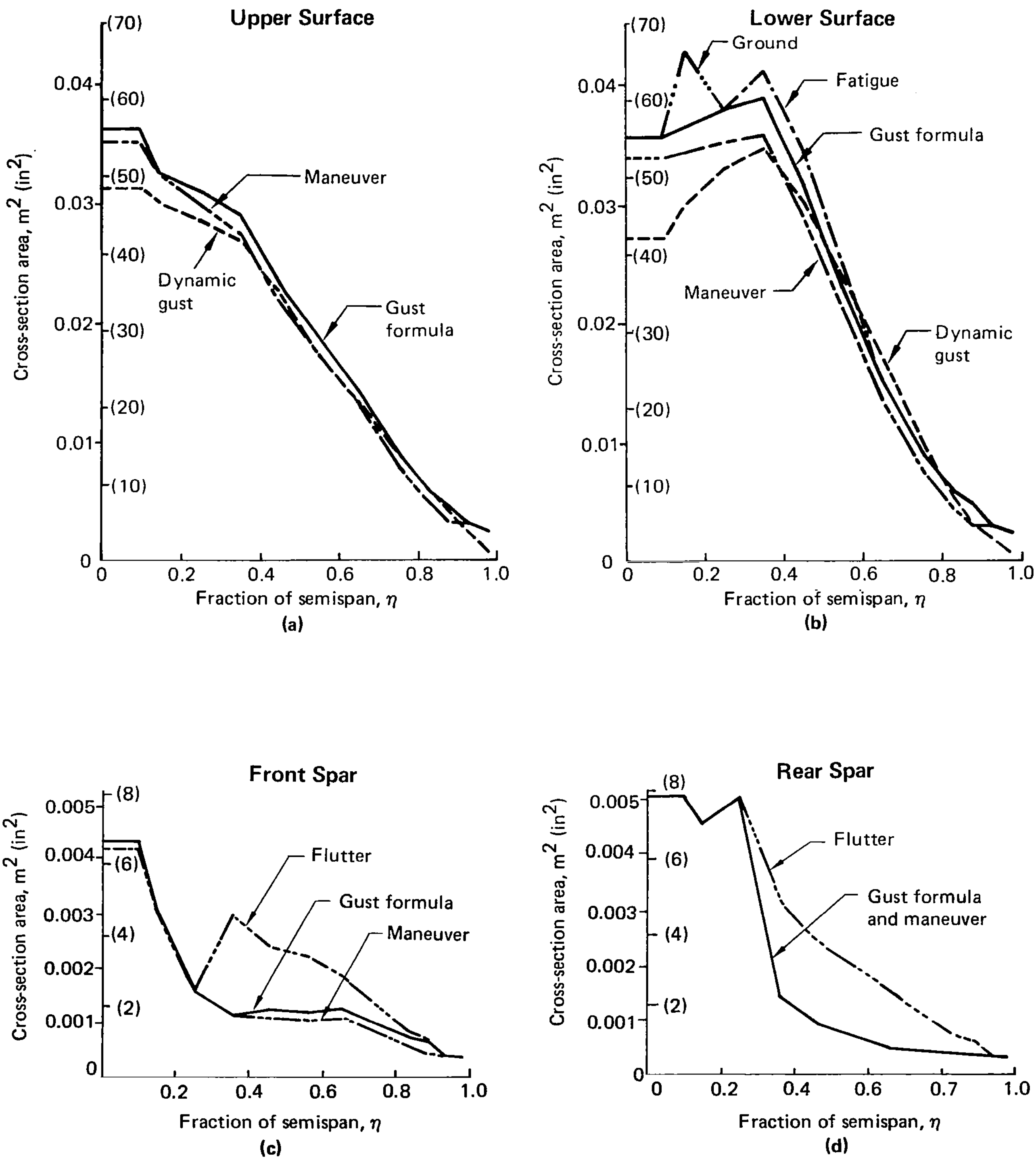


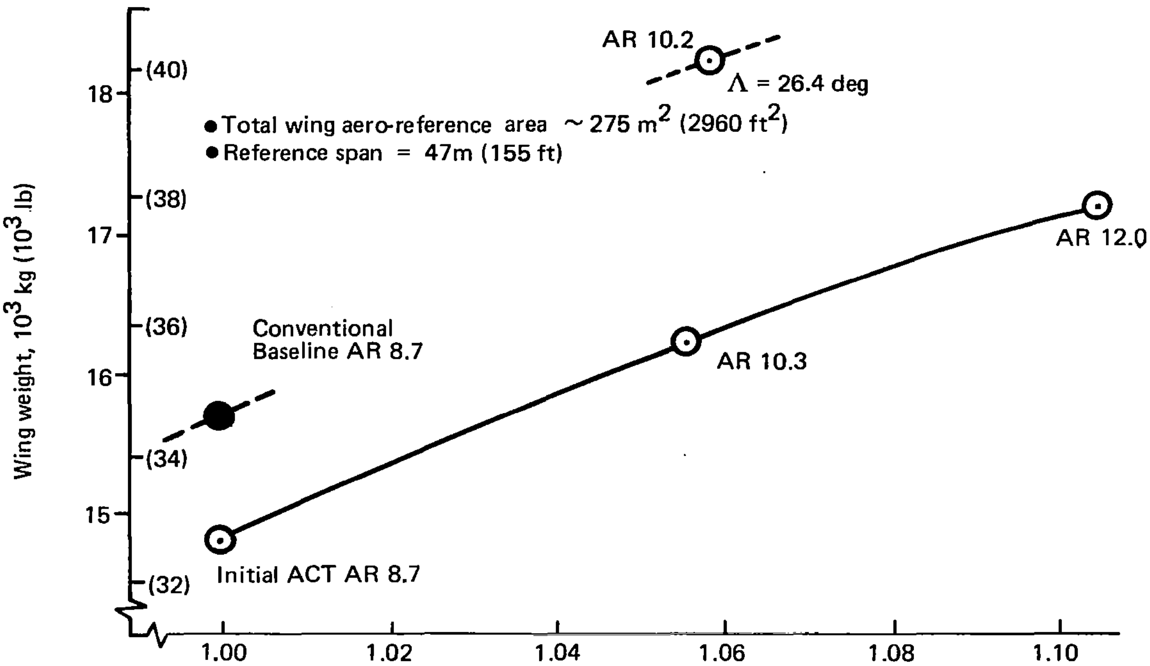

*Figure 11. Summary of Wing Material Requirements, Model 768-104 (AR 12, $\Lambda = 31.5$)*

## WING WEIGHTS AND RELATIVE OPERATING EMPTY WEIGHT

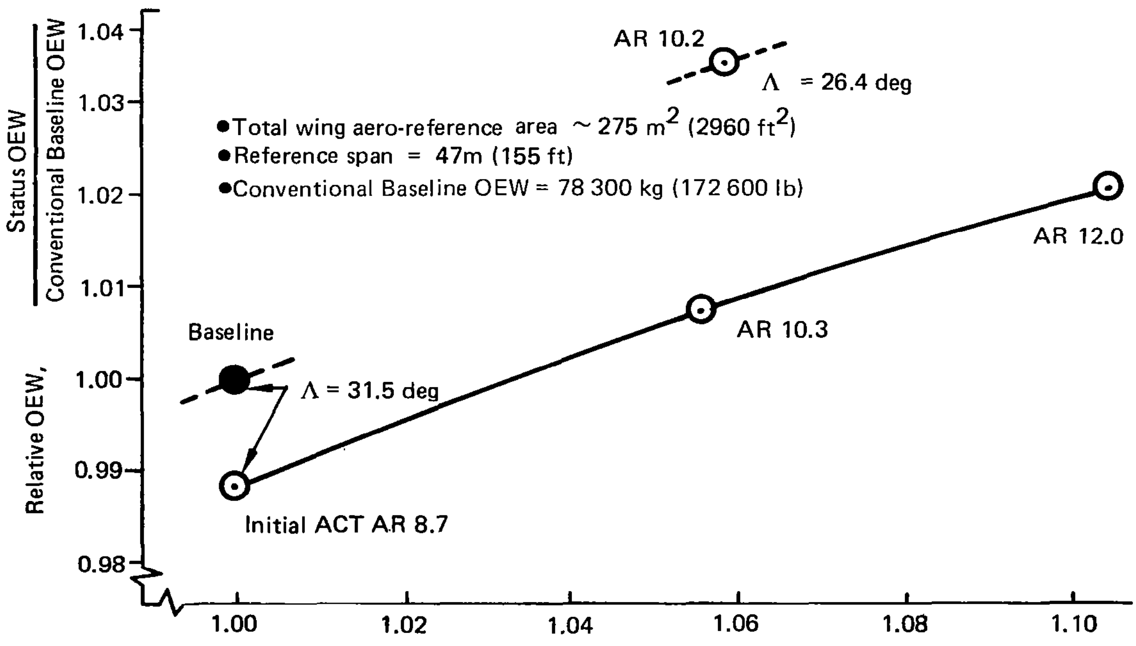
Figure 12(a) shows the total wing structural weight for all the airplanes examined during the IAAC Configuration activity. The Conventional Baseline was the starting point for each of these airplanes. The Initial ACT Configuration had a lighter wing with the identical planform of the Baseline. However, as the span was increased for the AR 10 and AR 12 configurations, wing weight increased with either reduced sweep or increased span. The wing weights shown in Figure 12(a) represent total wing structure including nonoptimum weight factors for fasteners, joints, pad ups, etc. The degree of weight benefit resulting from the incorporation of active controls is extremely configuration sensitive, so the weight trend shown for the active controls airplanes is applicable only to these configurations.

The change in cg limits and stabilizer size, made possible through the incorporation of pitch-augmented stability and angle-of-attack limiting, contributed approximately one-half of the weight savings shown in Figure 12(b). The remainder of the weight savings is due to wing weight reduction. The Initial ACT shows an empty weight decrease relative to the Conventional Baseline. As the wing span is increased, the weight increases to a value approximately 2% higher than the Baseline for the AR 12 configuration.

The reduced sweep AR 10 wing weight appears significantly higher because it was necessary to thin the wing to maintain the cruise Mach number as the sweep was reduced.




(a)




(b)

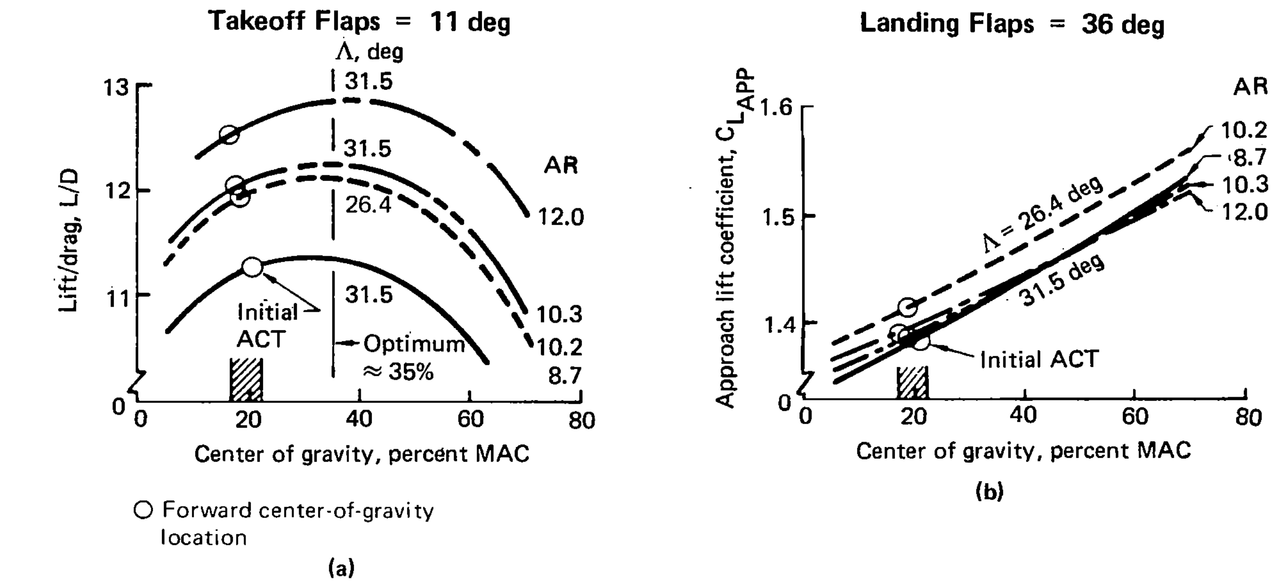
*Figure 12. Wing Weights and Relative Operational Empty Weight*

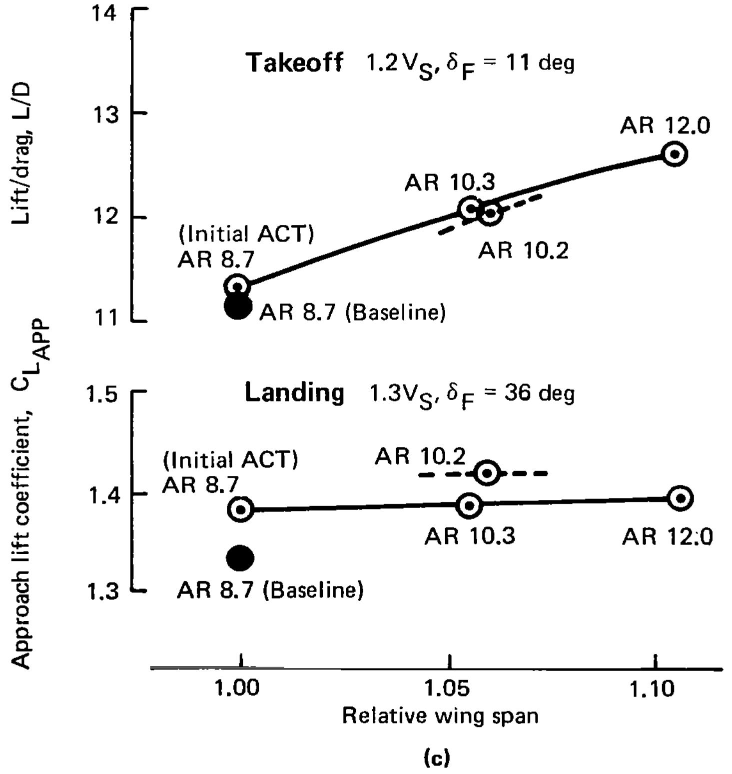
## LOW-SPEED AERODYNAMIC CHARACTERISTICS

Figure 13 shows the takeoff and landing aerodynamic characteristics for the Initial ACT and three Wing Planform Study Configurations in comparison to the Baseline Configuration. The L/D ratio for each of the ACT configurations at 11 deg takeoff flaps and forward cg (about 20% MAC) is approximately 2% less than the maximum attainable at optimum cg locations, as shown in Figure 13(a). However, the existing forward cg locations are near optimum for takeoff from a hot, high-altitude airport such as Denver or Mexico City.

Landing approach lift coefficients for all study configurations would benefit from farther aft forward cg limits. For example, about 5% improvement would result from moving the forward cg aft from 20% to 35% MAC, as shown in Figure 13(b).

The highest aspect ratio wing studied (AR 12, $\Lambda$ = 31.5 deg) exhibited about a 10% improvement in takeoff L/D over the Initial ACT Configuration. This was due primarily to lower induced drag. As shown in Figure 13(c), the AR 10, $\Lambda$ = 26.4 deg wing has a slightly lower takeoff L/D and a slightly higher approach lift coefficient than the AR 10, $\Lambda$ = 31.5 deg wing. Landing approach lift coefficient is essentially invariant for all the configurations with 31.5 deg swept wings.




| Forward cg limit, percent MAC | | | | |
|---|---|---|---|---|
| Center of gravity | 21.0 | 17.5 | 19.3 | 19.6 |
| Λ, deg | 31.5 | 31.5 | 31.5 | 26.4 |
| AR | 8.7 | 12.0 | 10.3 | 10.4 |

*Figure 13. Low-Speed Aerodynamic Characteristics*

## CRUISE EFFICIENCY

Figure 14(a) shows the relative cruise efficiencies of the Conventional Baseline, Initial ACT, and the three Wing Planform Study Configurations. Cruise L/D for each of the ACT configurations improved approximately 1% due to the approximately 10% aft shift in cruise cg, and about 2.5% due to the 45% reduction in horizontal stabilizer size. Both of these changes were made possible by the incorporation of pitch-augmented stability and angle-of-attack limiting. The nature of this cruise drag improvement for the Initial ACT is illustrated in Figure 14(a). The Wing Planform Study Configurations, having greater spans than the Baseline or Initial ACT, have less induced drag and show up to a 6% improvement in cruise L/D, as shown in Figure 14(a). Most of the wing profile drag improvement of the thinner unswept wing was offset by increased empennage size.

Figure 14(b) shows the cruise L/D improvements versus span. Total wetted area and wing area are approximately the same for all the Wing Planform Study Configurations and the Initial ACT. Fundamentally, L/D is a function of wing span and total airplane wetted area, although trim drag can be quite significant, as discussed above. With airplane wetted area approximately constant, L/D is predominantly a function of wing span. The highest aspect ratio configuration (AR 12) shows approximately 10% improvement in L/D over the Conventional Baseline due principally to three effects: lower trim drag, reduced tail size, and increased wing span.

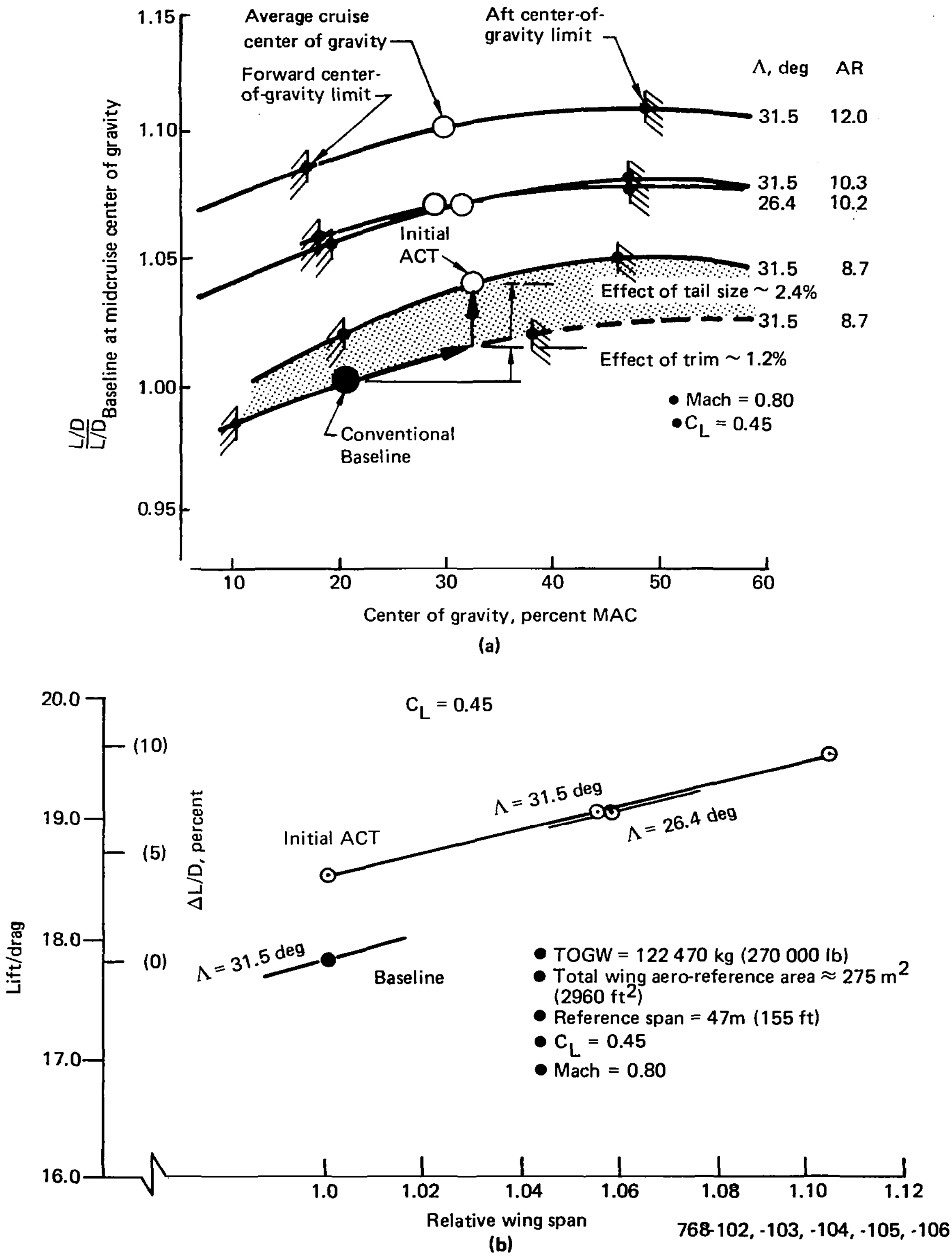



*Figure 14. Cruise Efficiency*

## BLOCK FUEL SAVINGS

The principal figure of merit for the performance of the ACT configurations developed under the IAAC Project is the relative block fuel required to accomplish the mission of the Conventional Baseline Configuration. As previously noted, the increased wing span of the high aspect ratio active controls configurations resulted in higher empty weights and higher L/D. Figure 15(a) shows how these effects translate into relative block fuel per passenger mile as a function of wing span. Note that even though the highest aspect ratio wing was heavier, its improved L/D more than offset the weight increase and resulted in reduced fuel requirements relative to the Baseline at the Baseline design range. Each of the configurations in Figure 15(a) exhibits a different maximum range for a fixed takeoff gross weight.

For comparison with the Baseline Configuration at its design mission, the best of the planform study configurations (AR 12, $\Lambda$ = 31.5) was resized to accomplish the Baseline mission. The resulting configuration, called Final ACT, yielded the fuel savings shown in Figure 15(b). The block fuel savings realized by the Final ACT Configuration relative to the Baseline are 10% at the design range and about 5% at short ranges. This figure also compares block fuel savings for the Final ACT and the Initial ACT Configurations.

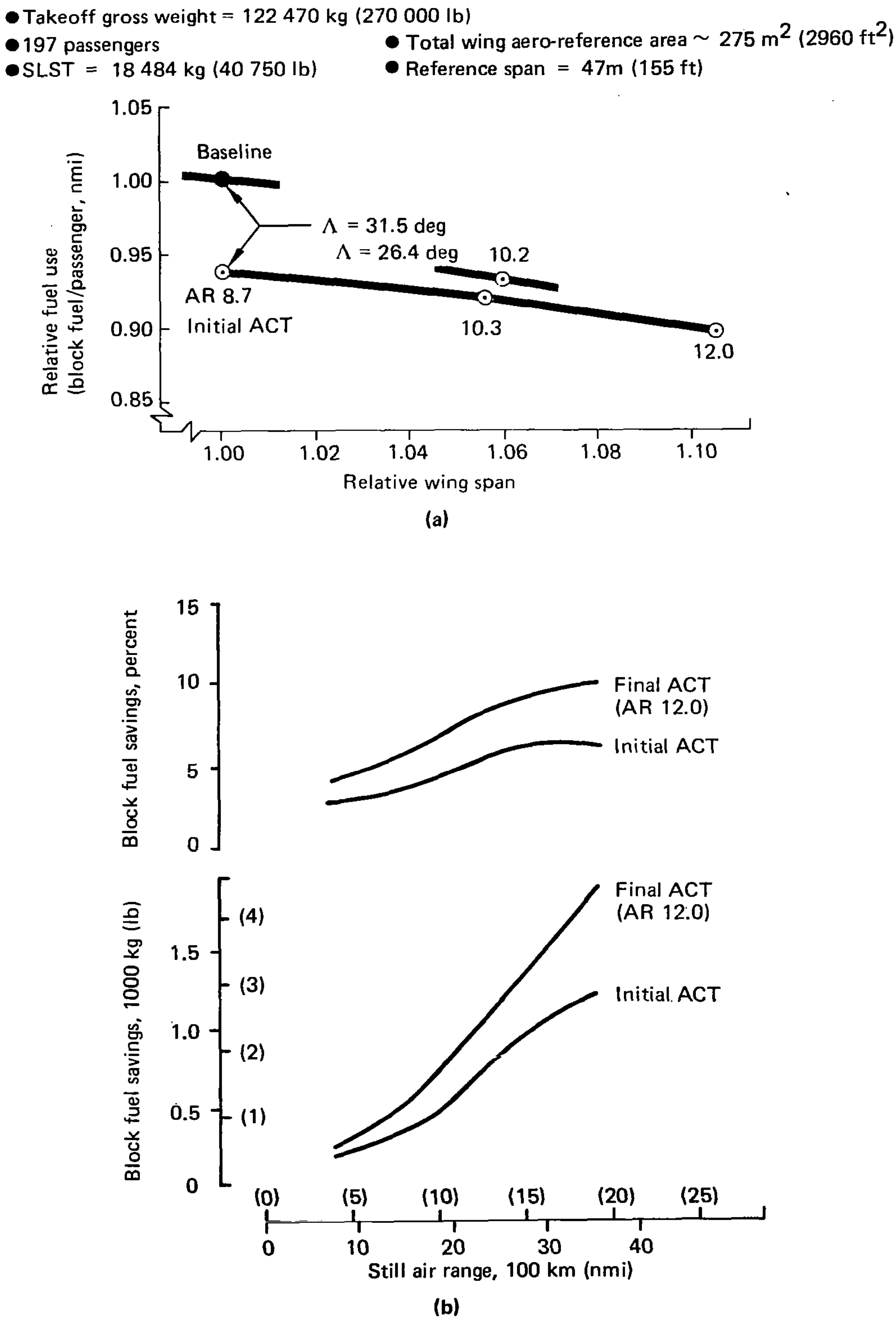



*Figure 15. Block Fuel Savings*

## CONVENTIONAL BASELINE AND FINAL ACT COMPARISON

The Final ACT Configuration is the AR 12 configuration resized to the Baseline mission. The plan and front view comparisons of the AR 8.7 Baseline and AR 12 Final ACT Configurations in Figure 16 show the principal external changes for the active controls configuration to be:

- Wing shifted forward 1.68m (66 in), cg moved aft relative to wing MAC
- Smaller tail size (PAS and AAL)
- Higher wing span with more taper

In addition, a different main landing gear design is used in the Final ACT Configuration to accommodate the farther aft cg range.

The Final ACT Configuration performance improvements, relative to the Baseline, are shown in the table of Figure 16. The increased wing span of the Final ACT Configuration, relative to the Conventional Baseline, required a 2% increase in empty weight and a slight increase in wing area, but yielded a 9.8% increase in cruise L/D. There was no change in engine size.

Takeoff field performance improved 15%, due principally to better climb performance resulting from trim drag reduction and lower drag due to lift (higher span). There was a slight reduction in approach speed and a 10% reduction in block fuel, as previously discussed.

Off-design mission performance can be an important factor in marketing a commercial transport. For example, airlines operating out of Denver may prefer an airplane with the full payload-range capability available for the high-altitude, hot-dry conditions often encountered during the summer. The active controls and greater span of the Final ACT Configuration make this possible, yielding 51% greater range out of Denver than the Conventional Baseline Configuration.

- SAR = 3590 km (1938 nmi)
- 197 passengers
- Cruise Mach = 0.80

| | Baseline | Final ACT | Δ, percent |
|---|---|---|---|
| MTW, kg (lb) | 122 920 (271 000) | 122 035 (269 040) | -0.7 |
| TOGW, kg (lb) | 122 470 (270 000) | 121 580 (268 040) | -0.7 |
| OEW, kg (lb) | 78 295 (172 610) | 79 885 (176 120) | 2.0 |
| Wing area, $m^2$ ($ft^2$) | 275 (2 961) | 276 (2 969) | 0.3 |
| Engine size, kg (lb) | 18 485 (40 750) | 18 485 (40 750) | 0 |
| L/D ($C_L$ = 0.45, M = 0.80) | 17.82 | 19.57 | 9.8 |
| TOFL [SL 29°C (84°F)], m (ft) | 2 210 (7 250) | 1 890 (6 200) | -15.0 |
| $V_{APP}$, m/s (kn) (maximum LW) | 70 (136.1) | 69 (134.2) | -1.4 |
| Block fuel, kg (lb) | 19 925 (43 930) | 17 920 (39 500) | -10 |
| Denver performance | | | |
| SAR [1625m (5334 ft), 33.33°C (92°F)], km (nmi) | 2 370 (1 280) | 3 590 (1 938) | 51 |

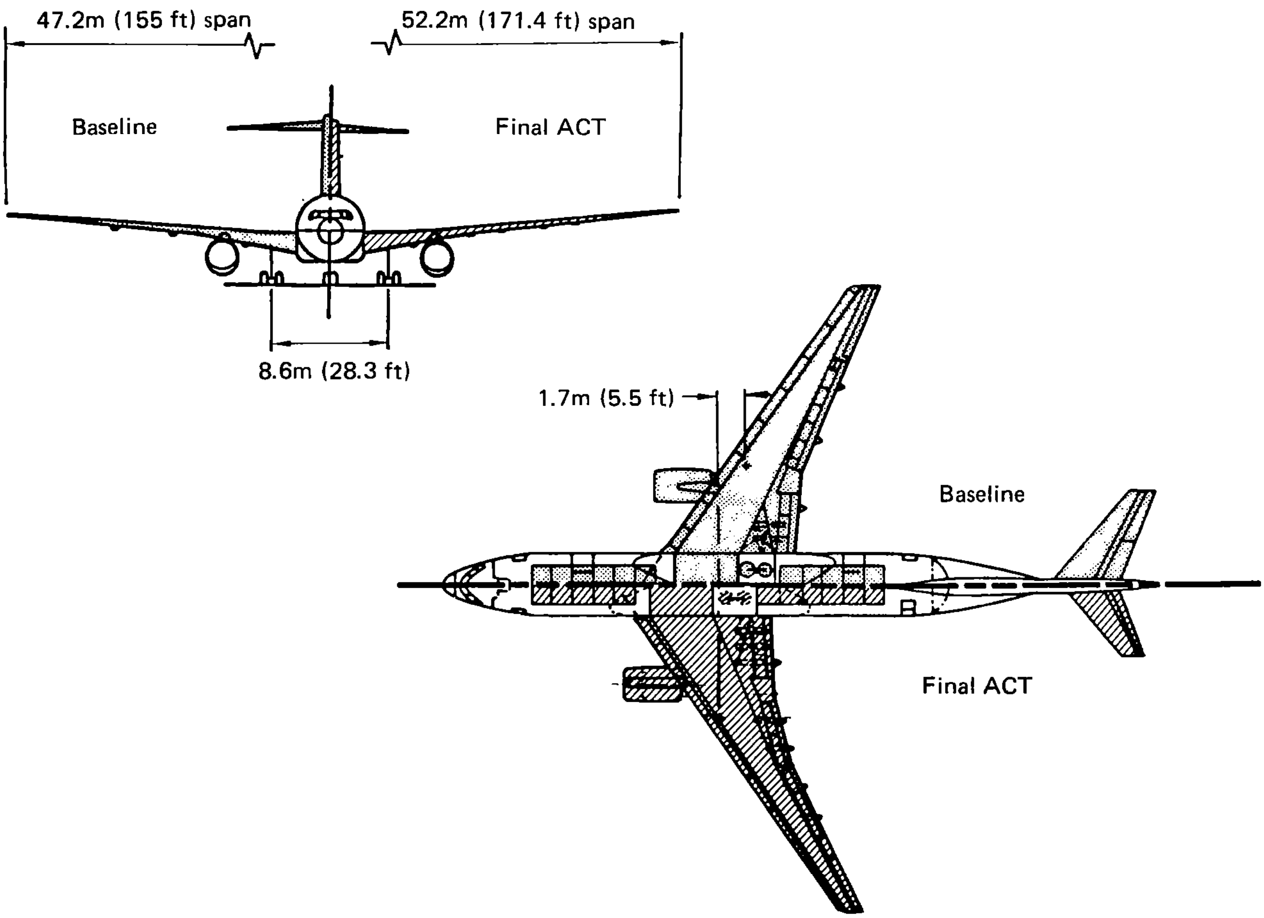



*Figure 16. Conventional Baseline and Final ACT Comparison*

## IN RETROSPECT

The specific performance benefits of ACT are very configuration sensitive, but for the types of airplanes examined under the IAAC Project, several observations merit special mention. As shown in Figure 17, PAS and AAL functions are the most important sources of block fuel reduction. The percentage of fuel efficiency improvement due to these functions appears essentially constant for the airplanes studied. This suggests that PAS and AAL should be the ACT functions to receive priority development.

ACT—either by itself or in concert with increased wing span—can be used to produce significant reduction in block fuel per passenger mile. The use of ACT—without any change in wing span—should not impact ground operation.

Increased wing span is often beneficial to a transport airplane's cruise performance and has been shown to be very significant for an ACT airplane where the increased span can be provided with less structural material than otherwise would be required. However, increased wing span may impact the ground operation of the airplane at airports where ramp and gate access is affected by wing span.

The Initial ACT Configuration exhibited 6.5% better fuel efficiency (at the design range of the Conventional Baseline) with the same wing span as the Conventional Baseline Configuration. Therefore, it could operate in and out of the same gates as the Conventional Baseline without additional ground operation restrictions. The Final ACT Configuration showed a 10% improvement in fuel efficiency that was due, in part, to the increased wing span, but this greater wing span would have some impact on the gate availability at certain airports. For example, at Chicago's O'Hare Airport, 7% fewer gates would be available to the Final ACT Configuration than were available to the Conventional Baseline Configuration or the Initial ACT Configuration. The fuel efficiency benefit of increased span must be weighed against a reduction in gate availability. The outcome of such considerations will, of course, be significantly influenced by fuel availability and price.

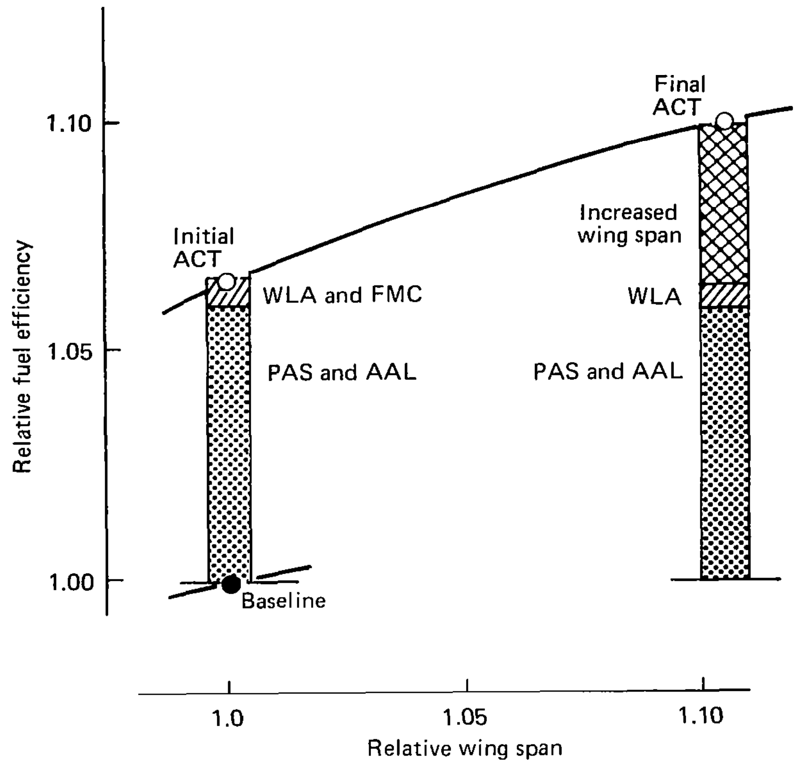



*Figure 17. ACT Function Fuel Efficiency Benefits, Relative to Baseline*

## CONCLUDING REMARKS

The configuration design and evaluation activities of the IAAC Project focused on configurations suitable for medium-range missions because they constitute a major share of domestic airline operations and, thereby, have high total fuel usage. Specifically, the Conventional Baseline Configuration was designed to a 197-passenger, nominal 3590 km (1938 nmi) design range mission requirement. A two-engine, seven-abreast seating configuration was selected because large analytical and wind tunnel test data bases were available. The design requirements and objectives for that configuration were evaluated and modified as appropriate to allow for the expected impact of ACT.

A Final ACT Configuration was developed from the AR 12, $\Lambda$ = 31.5 deg Wing Planform Study Configuration and has essentially identical geometry, the same engines, and the same passenger and cargo capacity. The only resizing of the AR 12 wing configuration necessary consisted of an 890 kg (1960 lb) reduction in takeoff gross weight and an associated 70 kg (160 lb) reduction in operating empty weight. These changes reduced the range to that of the Conventional Baseline Configuration; i.e., 3590 km (1938 nmi). This allowed a direct comparison of the Final ACT Configuration with the Conventional Baseline and showed a 10% reduction in block fuel (at design range) due to active controls and the increased wing span. The resulting configuration is shown in Figure 18.

The most beneficial ACT functions on the Final ACT Configuration were the pitch-augmented stability and angle-of attack-limiter systems. Block fuel savings of 6% were directly related to these functions; the remaining fuel savings were due to maneuver-load control and increased wing span. The wing-load alleviation system, although not showing large benefits for the particular configuration being discussed here, may produce more significant improvements for other configurations or growth derivatives.

The airplane performance benefits identified in the IAAC Project to date are the result of a degree of dependence upon control systems that is well beyond any currently certified commercial airplane. Considerable design, development, and laboratory and flight test must precede a commitment to commercial application. Work currently underway on the IAAC Project is the beginning of this necessary development and test.

| | |
|---|---|
| Passengers<br>Mixed class<br>All tourist | <br>197<br>207 |
| Containers | (22) LD-2,<br>or (11) LD-3 |
| Engines | (2) CF6-6D2 |
| Weights<br>TOGW, kg (lb)<br>OEW, kg (lb) | <br>121 580 (268 040)<br>79 890 (176 120) |
| Range, km (nmi) | 3 590 (1 938) |

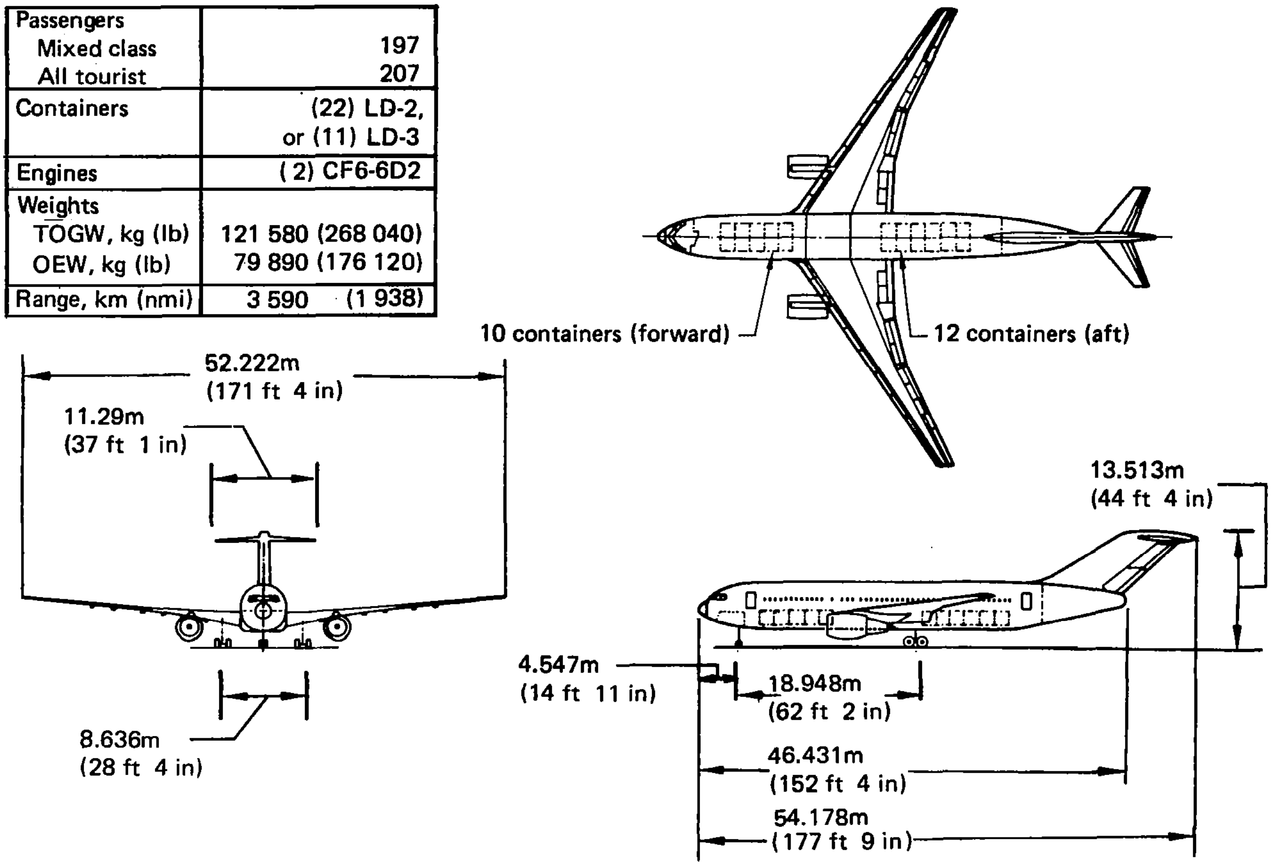



*Figure 18. Final ACT Configuration*

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15. Supplementary Notes

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Topical Report

16. Abstract

This report summarizes the Wing Planform Study Task and Final Configuration Selection of the Integrated Application of Active Controls (IAAC) Technology Project within the Energy Efficient Transport Program. Application of Active Controls Technology (ACT) in combination with increased wing span resulted in significant improvements over the Conventional Baseline Configuration (Baseline) and the Initial ACT Configuration previously established. The configurations use the same levels of technology (except for ACT), takeoff gross weight, and payload as the Baseline. The Final ACT Configuration (Model 768-107) incorporates pitch-augmented stability (which enabled an approximately 10% aft shift in cruise center of gravity and a 45% reduction in horizontal tail sizes), lateral/directional-augmented stability, an angle-of-attack limiter, and wing-load alleviation. Flutter-mode control was not beneficial for this configuration. This resulted in an 890 kg (1960 lb) reduction in airplane takeoff gross weight and a 9.8% improvement in cruise lift/drag. At the Baseline mission range (3590 km) (1938 nmi), this amounts to 10% block fuel reduction. Good takeoff performance at high-altitude airports on a hot day was also achieved. Results of this task strongly indicate that the IAAC Project should proceed with the Final ACT evaluation and begin the required control system development and testing.

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